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Climate change effects on the frequency, seasonality and interannual variability of suitable prescribed burning weather conditions in south-eastern Australia

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ABSTRACT

Despite the importance of prescribed burning in contemporary fire management, there is little understanding of how climate change will influence the weather conditions under which it is deployed. We provide quantitative estimates of potential changes in the number of prescribed burning days in coastal NSW in south-eastern Australia, a fire-prone area dominated by dry sclerophyll forests. Burning days are calculated from an objectively designed regional climate model ensemble using three definitions of suitable weather conditions based on: a literature search (Literature), actual weather observed during recorded prescribed burns (Observed) and operational guidelines (Operational). Contrary to some claims, evidence for a decrease in prescribed burning days under projected future climates is weak. We found a complex pattern of changes, with the potential for substantial and widespread increases in the current burning seasons of autumn (March-May) and spring (August-October). Projected changes were particularly uncertain in northern NSW, spanning substantial increases and decreases during autumn. The magnitude of projected changes in the frequency of burning days was highly sensitive to which definition of suitable weather conditions was used, with a relatively small change for the Operational definition (+0.3 to +1.9 days per year across the study area) and larger ranges for the Observed (+0.2 to +7.9 days) and Literature (+1.7 to +6.2 days) definitions. Interannual variability in the number of burning days is projected to increase slightly under projected climate change. Our study highlights the need for a better understanding of the weather conditions required for safe and effective prescribed burning. Our analysis provides practitioners with quantitative information to assess their exposure to a range of potential changes in the frequency, seasonality and variability of prescribed burning weather conditions.

1. Introduction

Contemporary fire management is subject to a range of pressures, including an expanding wildland-urban interface (Radeloff et al., 2018), declining volunteer numbers (Baxter-Tomkins, 2011; Gutierrez and Cassidy, 2018) and increasing attention to the impacts of smoke (Williamson et al., 2016). Prescribed burning, the practice of altering fuel properties to achieve various management objectives, provides a focal point for many of these pressures (Fernandes and Botelho, 2003; Penman et al., 2011). Although its effectiveness at mitigating these risks remains an area of active research (Furlaud et al. (2018); Holland et al., 2017; Price et al., 2015), prescribed burning is a central component of fire management around the world (Moritz et al., 2014). In south-eastern Australia, there is significant investment in the practice, sometimes with mandated targets in area burned or proportion of the landscape treated (NSW Government, 2017; Teague et al., 2010).

A wide range of factors go into the planning of a prescribed burn, including vegetation type, desired fire intensity, rate of spread and extent, site properties such as topography, hazards and proximity to people and property, smoke management and operational management considerations (Office of Environment and Heritage NSW, 2017). However, as with wildfire, weather conditions play a critical role throughout the process, influencing the moisture content and flammability of the fuel (Boer et al., 2018), fire behaviour (McArthur, 1962,

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Table 1
Examples of variables used in dry sclerophyll forest prescribed burning weather definitions.

Standard weather variables	Other variables	Source
Temperature, relative humidity, wind speed		Cheney, 1978
Temperature, relative humidity, wind speed	KBDI, FFDI two day outlook, fuel moisture	Tolhurst and Cheney, 1999
Temperature, relative humidity, wind speed, wind direction		Southeast Queensland Fire and Biodiversity Consortium (2002)
Temperature, relative humidity, wind speed	FFDI, fuel moisture	Marsden-Smedley, 2009, 2011
Temperature, relative humidity, wind speed	atmospheric stability, FFDI	NSW RFS[a]

[a] https://www.rfs.nsw.gov.au/_data/assets/pdf_file/0011/13322/Standards-for-Low-Intensity-Bush-Fire-Hazard-Reduction-Burning.pdf (Accessed 15 May 2018).

1967), smoke transport (Price et al., 2016) and the possibility of re-ignition (NSW RFS, 2017). A key component of prescribed burn plans is therefore the specification of weather conditions that allow fires to burn at a controllable intensity i.e. within prescription. Specifications often take the form of an envelope or window of desirable conditions through the use of lower and upper thresholds for weather variables. This leads to a situation where being too close to the lower bounds of the weather envelope is associated with the risk that the fire will not burn well enough to reduce the fuel load to the target level, while exceeding the upper end of the weather envelope is associated with too great a risk of a fire escaping (Enright and Fontaine, 2013; Esplin et al., 2003). A further consideration at the upper bounds of the weather envelope is that fire management resources may be redirected to wildfires instead of prescribed fire. As a consequence, prescribed burns in forests usually occur in autumn and spring.

Weather definitions may be developed for specific vegetation types or modified based on site properties such as fuel amount or fuel moisture. A number of weather definitions have been developed for dry sclerophyll forest, the dominant vegetation type subject to prescribed burning in temperate Australia (Table 1). Temperature, relative humidity and wind speed appear in all definitions. Wind direction and atmospheric stability are often cited in discussions about appropriate weather conditions for prescribed burning but actual values of these variables are specified in only two definitions listed here. The McArthur Forest Fire Danger Index (FFDI; Luke and McArthur, 1978), calculated from air temperature, relative humidity, wind speed and precipitation, is commonly included. FFDI incorporates a measure of soil moisture deficit, either the Keetch Byram Drought Index (KBDI; Keetch and Byram, 1968) or Mount's Soil Dryness Index (SDI; Mount, 1972). These soil moisture measures are used to compute a Drought Factor (DF) which represents fuel moisture, a variable that is listed in its own right in several definitions (Noble et al., 1980). While fuel moisture can be measured in the field, weather-based predictions capture important properties as they relate to fire behaviour or impact (Matthews, 2014; Resco de Dios et al., 2015; Sharples et al., 2009), so we include it as a weather-related variable here. The Canadian Forest Fire Weather Index System (FWI; Van Wagner, 1987) has been used as a basis for prescribed burning weather definitions in Canada and Europe, while in the United States definitions draw on the National Fire Danger Ratings System (NFDRS; Deeming et al., 1978).

The size of the current window of opportunity to conduct prescribed burns in south-eastern Australia has been described as inherently small (Cowell and Cheney, 2017; Enright and Fontaine, 2013; Esplin et al., 2003; Penman et al., 2011), although there have only been intermittent and localised attempts to quantify its historical frequency and variability, often in Government or agency reports (ACT Government, 2009; Esplin et al., 2003; Gill et al., 1987; State Fire Management Council, 2014). Both within and between these studies, the reported number of suitable burning varies considerably (ranging from 1 to 100 days per year). These differences stem from factors such as weather, vegetation type and fuel amount, as well as the weather definition used. There have also been recent estimates of suitable agricultural burning conditions in Calakmul, Mexico (Monzon-Alvarado et al., 2014) and weather conditions promoting dispersion of prescribed burning smoke in the south-eastern U.S. (Chiodi et al., 2018).

Little is yet known about the impact of climate change on the frequency of suitable weather conditions for prescribed burning in south-eastern Australia. While there has been considerable research into climate change impacts on fire weather conditions (e.g. Flannigan et al., 2009 and references therein), it has largely been restricted to average conditions or the extreme fire weather under which the greatest loss of life and property has occurred (Blanchi et al., 2010, 2014). What reference has been made to prescribed burning weather conditions is generally brief and qualitative, with suggestions that the window could decrease (Prichard et al., 2017), decrease or increase (Wimberly and Liu, 2014) or that it is already decreasing (Williamson et al., 2016; Ximenes et al., 2017). Possible reasons for future declines in burn windows include a decrease in the coincidence of suitable weather and fuel moisture due to increasing climate variability (Mitchell et al., 2014) and the fire season starting earlier and lasting longer (Harris et al., 2016). The possibility has also been raised of little change in the frequency of suitable prescribed burning days, but a change in seasonality towards winter (Rocca et al., 2014). The development of quantitative estimates is thus an important step towards investigating these hypotheses, formalising the problem and highlighting areas of uncertainty and future research. One quantitative analysis in south-eastern Australia found a large range of potential changes in burn windows, about ± 10 days in autumn, and -10 to +3 days in spring (Clarke and Evans, 2018). However, there were some regions where only decreases in the number of spring burning days were projected. A limitation of this study is that it used a single, simple proxy for suitable burning days (FFDI between 3 and 12). Assessing more complex and realistic weather definitions will give a better indication of sources of uncertainty in these projections and may improve the salience of such estimates for decision makers in fire and land management agencies.

Notwithstanding the complex array of natural and anthropogenic factors that influence prescribed burning, the availability of suitable weather conditions may limit fire agencies' ability to use this tool. This is particularly significant given the possibility of an increased role for prescribed burning in the future, for example in response to increased fire risk (Khabarov et al., 2016; Krofcheck et al., 2018; Tarancon et al., 2014) or as a way to mitigating greenhouse gas emissions (Bradstock et al., 2012). Here we aim to quantitatively assess the impacts of climate change on prescribed burning weather conditions in south-eastern Australia using multiple weather definitions. Specifically we address the following research questions:

- Will the average number of suitable prescribed burning days decrease under climate change?
- Will the seasonality of suitable prescribed burning days shift under climate change?
- Will climate change affect interannual variability in the number of suitable prescribed burning days?
- Are there regional differences in projected changes to the frequency, variability and timing of suitable prescribed burning days?

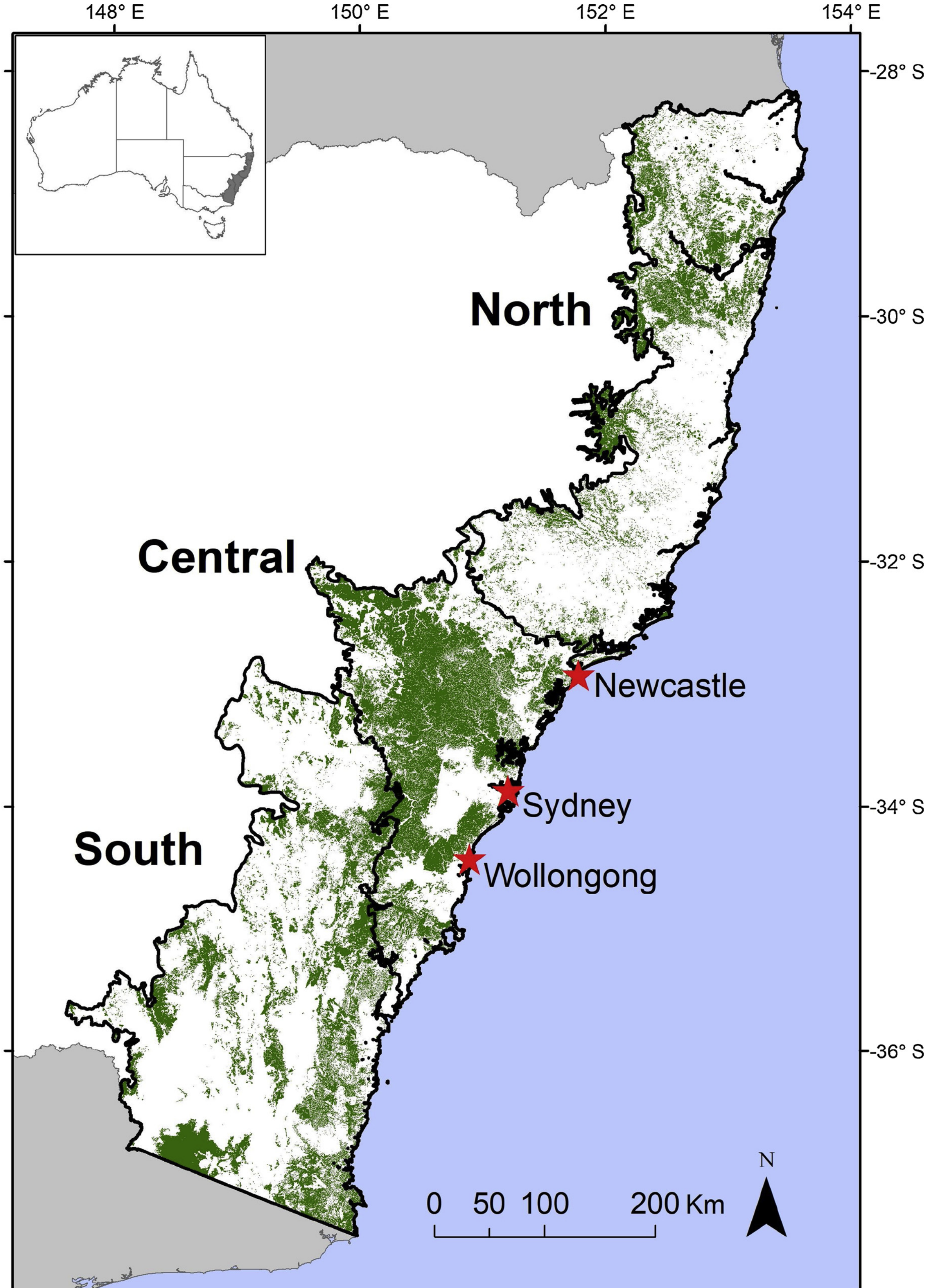

Fig. 1. Location of study area in the south-eastern Australian State of NSW. The entire study area is referred to as Coastal NSW and comprises South, Central and North regions. The green shaded area represents Dry Sclerophyll Forest (DSF; Keith, 2004) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

2. Methods

2.1. Study area

The study focuses on the coastal region of New South Wales ("Coastal NSW") in south-eastern Australia (Fig. 1). It comprises South, Central and North regions, with boundaries based on the Interim Biogeographic Regions of Australia (Hutchinson et al., 2005). The majority of the NSW population lives in this region, with large urban centres in Sydney, Newcastle and Wollongong. The region contains most of the state's dry sclerophyll forest and a large amount of wildland urban interface. The climate is predominantly temperate, except for the far north where it is subtropical (www.bom.gov.au, accessed 20 August 2018). The study area is roughly split into two rainfall seasonality zones. In the north and patches of the south, rain falls mostly in summer and winters are dry. In most of the south, rainfall is spread more uniformly throughout the year.

2.2. Prescribed burn data

Prescribed burn locations and dates were compiled from fire history mapping maintained by the NSW National Parks and Wildlife Service (NPWS), from 2004 to 2015. We restricted our analysis to prescribed burns undertaken in areas with at least 90% Dry Sclerophyll Forest (DSF; Keith, 2004). This resulted in 2343 burn records. Some statistics of prescribed burning in NSW are shown in Table 2. The vast majority of burns were undertaken in autumn (March-May; n = 1,022, 44% of all burns) and spring (defined here as August-October; n = 1,071, 46% of all burns).

2.3. Weather definitions

Three different weather definitions were used to assess the frequency of suitable prescribed burning days: Literature, Observed and Operational (Table 3). The Literature definition was created based on a review of the sources cited in Table 1. Upper and lower limits were set for temperature, humidity, FFDI and fuel moisture. Upper limits were also set on three day outlooks for wind speed and FFDI to represent the risk of re-ignition or escape of a pre-existing burn. Atmospheric stability was not included because only one source used it (NSW RFS) and did not provide clear guidelines on its definition or measurement. Furthermore, the validity and applicability of the most widely known atmospheric stability index, the Haines Index, has been questioned (Potter, 2018).

The Observed definition used the same variables and the same combination of upper and lower thresholds as the Literature definition, but the values were derived from observed weather conditions during actual prescribed burns in DSF in NSW over the period 2004–2015 (see Section 2.2). Estimates of daily maximum temperature and relative humidity at time of maximum temperature were drawn from the SILO database (Jeffrey et al., 2001), a gridded product based on station observations with ˜5 km resolution. Fine dead fuel moisture content for the dates and location of recorded prescribed burns was predicted from daily maximum temperature and relative humidity following Resco de Dios et al. (2015) and Nolan et al. (2016). As SILO does not include wind speed, daily 3 pm wind speed and FFDI values were drawn from the nearest Bureau of Meteorology weather station. Three quarters of all records were within 20 km of the prescribed burn location, with a maximum distance of 70 km (1 record). Lower and upper thresholds were set using the 10th and 90th percentile values from the distribution of each variable.

The Operational definition was based on unpublished NPWS guidelines for prescribed burning in DSF. We used the generic version but there are also regional variants. The Operational definition had a narrower fuel moisture range and lacked lower and upper thresholds for more variables than the Literature and Observed definitions.

Table 2
Features of dry sclerophyll forest prescribed burning from 2004 to 2015 in NSW (compiled from fire history mapping maintained by the NSW National Parks and Wildlife Service).

	Mean	Range
Number of burns per year	184	13 – 299
Burned area per year (ha)	23,084	1,186 – 75,654
Annual mean fire size (ha)	114	31 – 253
Annual median fire size (ha)	9.8	3.3 – 31.0

Table 3
Weather definitions used. The Literature definition is based on a literature review, the Observed definition is based on 10th and 90th percentile values from the distribution of weather during actual burns and the Operational definition is drawn from operational guidelines.

		Literature	Observed	Operational
Maximum temperature (°C)	Min	18	16.5	*n/a*
	Max	27	28.5	25
Relative humidity (%)	Min	35	30.7	45
	Max	70	56.4	*n/a*
Wind speed (km/h)	Max	20	24.1	10
Wind speed 3 day outlook (km/h)	Max	20	27.7	*n/a*
FFDI	Min	1	1.9	*n/a*
	Max	12	12.9	8
FFDI 3 day outlook	Max	12	15.2	24
Fuel moisture (%)	Min	9	9.1	13
	Max	16	17.1	16

2.4. Climate projections

Climate projections were sourced from the NSW and ACT Regional Climate Modelling (NARCliM) project (Evans et al., 2014). NARCliM projections are based on version 3.3 of the Advanced Research WRF (Weather Research and Forecasting) regional climate modelling system (Skamarock et al., 2005). WRF has previously been used in this region to simulate fire weather (Clarke et al., 2013) and climate more generally (Evans and McCabe, 2010, 2013). NARCliM's 12 member ensemble comprises four Global Climate Models (CCCMA3.1, CSIRO-MK3.0, ECHAM5, MIROC3.2) downscaled using three configurations of WRF (RCM 1, 2 and 3). All models were selected to maximise model skill and independence and to span the range of future change in precipitation and temperature over NSW. Due to resourcing and computational constraints only one emissions scenario, SRES A2, was used for future projections (Nakicenovic et al., 2000). The A2 scenario has a similar trajectory in the late 21 st century to the newer scenario RCP8.5 (Moss et al., 2010). The simulations used in this paper covered two 20 year periods: 1990–2009 ('present') and 2060–2079 ('future'). The NARCliM ensemble has been evaluated and found to perform well in terms of general climate (Olson et al., 2016), the El Nino–Southern Oscillation (ENSO; Fita et al., 2017), extreme rainfall (Evans et al., 2017) and storm systems (Di Luca et al., 2016). The NARCliM ensemble captures existing variation between regions and between prescribed burning weather definitions well, but has an overall positive bias in the mean number and interannual variability of prescribed burning days (Supplementary Material).

2.5. Analysis

Input data for climate change analyses were 20 years of output from each member of the NARCliM ensemble for both present and future periods. Daily total precipitation, daily maximum temperature, daily 3 pm relative humidity and daily 3 pm wind speed were standard model output. These were used to predict daily fine dead fuel moisture (Resco de Dios et al., 2015; Nolan et al., 2016) and FFDI. Suitable prescribed

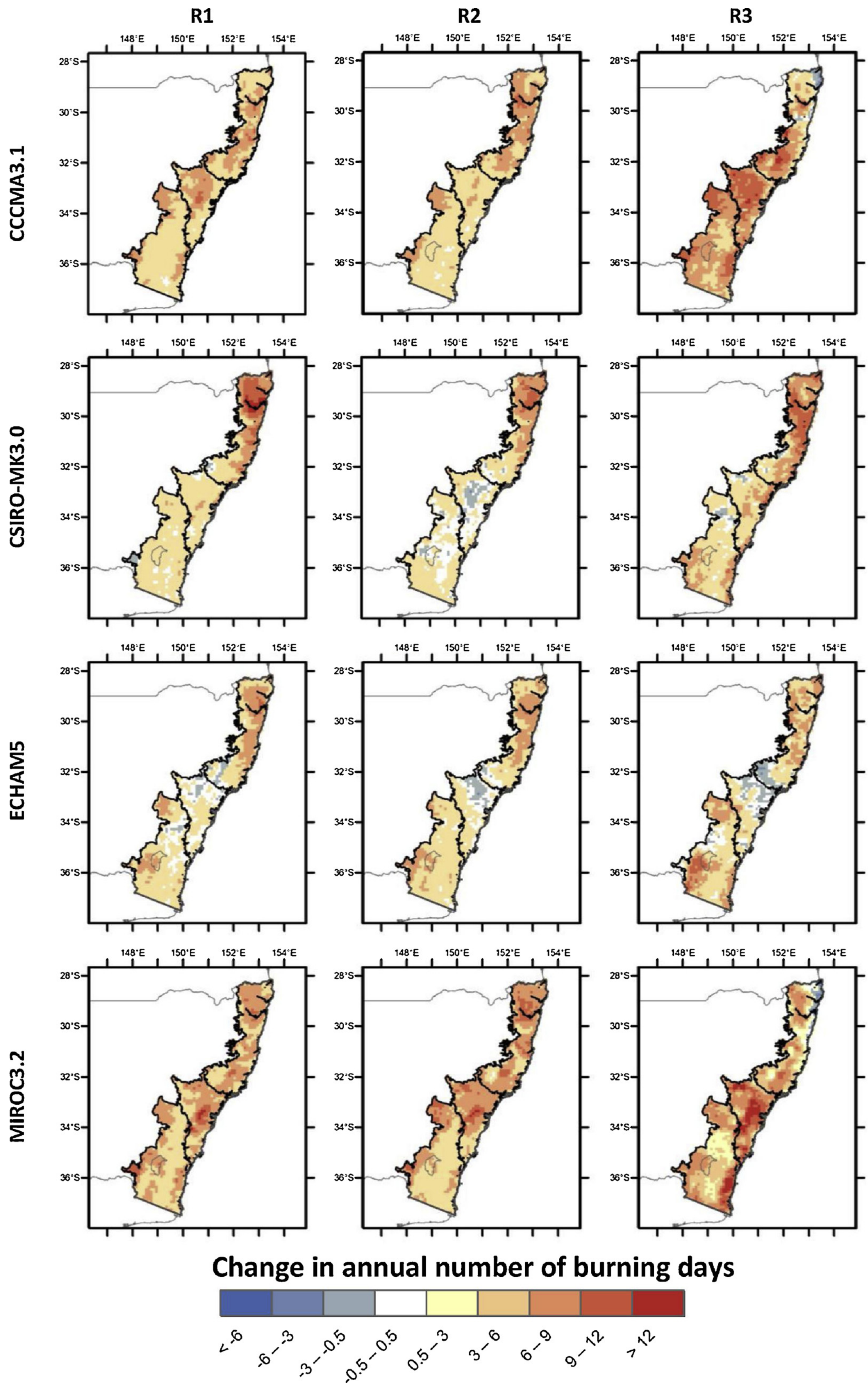

Fig. 2. Projected change in annual number of prescribed burning days, calculated using the Literature definition, for 2060–2079 relative to 1990–2009. The 12 member ensemble is derived from four global climate models (rows; CCCMA3.1, CSIRO-MK3.0, ECHAM5 and MIROC3.2) and three regional climate models (columns; R1, R2 and R3). Dark lines show boundaries of the South, Central and North regions, which together comprise Coastal NSW.

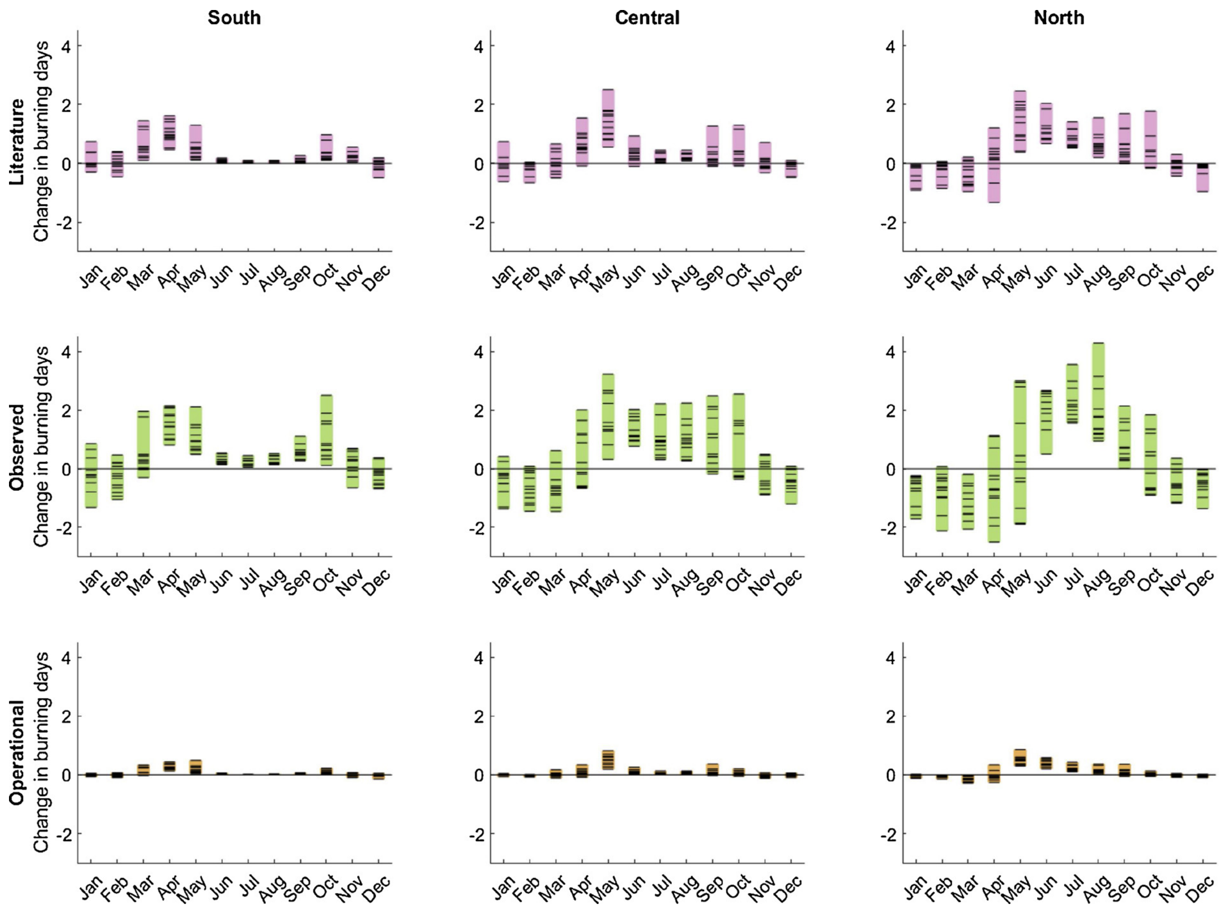

Fig. 3. Projected change in monthly number of prescribed burning days, calculated using the Literature, Observed and Operational definitions, for 2060–2079 relative to 1990–2009. Results are shown for the South, Central and North regions. Vertical bars show range across all models, horizontal lines represent individual models.

burning days were defined as days with weather conditions matching the Literature, Observed or Operational definitions (Table 3). These figures were calculated on an area average basis for the whole study area (Coastal NSW), North, Central and South regions, and on a per pixel basis. The projected change in prescribed burning days was calculated as the difference between future (2060–2079) and present (1990–2009) values for a given statistic. Variability in present and future annual prescribed burning days was represented by standard deviation.

3. Results

Increases in the annual frequency of suitable burning days based on the Literature definition were more widespread and greater in magnitude than decreases, which were largely limited to the Central region and the south of the North region (Fig. 2). Similar patterns in the spatial distribution and relative magnitude of increases compared to decreases were observed for the Observed and Operational definitions (Supp. Figs. 3,4). However, the magnitude of changes varied considerably between the three weather definitions (Fig. 3; Table 4). Annually and in the peak prescribed burning seasons of autumn and spring, projected changes to Operational burning days were uniformly positive (or zero) but much smaller in magnitude than the other two definitions. For example, the largest change across the 12 member ensemble for any region was +1.3 days in autumn, compared to a 1990–2009 baseline of 1.9 days for the same ensemble member. The largest spring increase was +0.8 days (baseline = 0.3 days) and the largest annual increase was +2.5 days (baseline = 3.0 days). In contrast, the largest change in burning days calculated with the Observed definition was +4.4 days in autumn (baseline = 14.2 days), +8.3 days in spring (baseline = 12.2 days) and +11.5 days annually (baseline = 25.8 days). The lower end of Observed burning day projections was also frequently less than the other two definitions, resulting in a much larger spread across the

Table 4
Lower (L) and upper (U) ensemble bounds of projected change in number of prescribed burning days per year and for the two major prescribed burning seasons, autumn (March-May) and spring (August-October), for 2060–2079 relative to 1990–2009. Burning days are calculated using the Literature, Observed and Operational definitions. Results are shown for the South, Central and North regions and for the entire study area (Coastal NSW).

		Change in prescribed burning days (2060-2079 relative to 1990-2009)					
		Literature		Observed		Operational	
		L	U	L	U	L	U
Annual	South	0.8	6.2	1.7	8.5	0.2	1.6
	Central	0.4	8.8	−3.3	11.5	0.2	2.5
	North	2.5	4.9	−5.4	10.3	0.4	1.8
	Coastal NSW	1.7	6.2	0.2	7.9	0.3	1.9
Autumn	South	1.1	3.4	1.9	3.9	0.3	1.0
	Central	0.7	3.2	−1.0	4.4	0.2	1.3
	North	−1.3	3.2	−6.2	3.7	0.0	1.0
	Coastal NSW	1.3	2.9	−0.8	3.8	0.2	0.8
Spring	South	0.1	1.2	1.0	3.9	0.1	0.3
	Central	−0.1	2.8	−0.1	6.9	0.0	0.7
	North	0.1	4.5	0.4	8.3	0.0	0.8
	Coastal NSW	0.1	2.6	0.5	6.1	0.0	0.6

ensemble annually and during both burning seasons for all regions except the South in autumn, when the spread for Literature burning days was slightly larger (2.3 vs 2.0 days). The Observed definition was the only one for which some ensemble members projected an annual decrease in the number of burning days (by up to −5.4 days in the North and −3.3 days in the Central region). It was also the definition for which the largest changes were projected.

Despite these differences in magnitude, the monthly pattern of changes was similar between the three definitions (Fig. 3). Decreases in all regions were clustered in summer; increases in the North were largely between May and September; the increases in the Central region were mostly between April and October and increases in the South were concentrated between March and May and in October. Annually and for the two major prescribed burning seasons, the vast majority of projections were increases. All models projected increases in burning days in the South, while most projected increases in the North, Central and the overall study area. The largest projected increases and smallest projected decreases were usually in spring, while there was relatively less model agreement during autumn. As with projected changes in mean values, interannual variability in prescribed burning days varied strongly between weather definitions, increasing in magnitude from the Operational to the Observed definitions (Fig. 4). Over the 20 year simulated future period, there were small but consistent increases in the standard deviation of annual burning days compared to the present day in most regions and weather definitions.

4. Discussion

There is not good evidence for a decrease in prescribed burning days under climate change. While there were some regions and time of year for which some ensemble members projected fewer burning days, more models projected relatively larger increases in more areas and times, particularly during the current peak burning seasons of autumn and spring. There was evidence for a change in the seasonality of weather conditions favourable to prescribed burning. Broadly speaking, there was a potential for widespread increases from April to October and similarly widespread decreases from November to March. There was some regional variation in projected changes to prescribed burning days. The magnitude and range of projected changes was generally smallest in the South region, however these changes were universally positive in autumn and spring. The projections for the North and Central regions were similar to each other, with potentially strong increases in spring but uncertainty over the direction of change in autumn. Modelled interannual variability in prescribed burning days was projected to increase moderately in many cases. Importantly, projected changes were highly sensitive to the weather definition used to calculate burning days. Choice of definition affected the direction, range and magnitude of the changes projected across the study area, although most changes fall within the bounds of existing interannual variability.

The quantitative estimates presented here complement previous, predominantly qualitative hypotheses of climate change impacts on prescribed burn windows. Our results lend support to accounts emphasising the uncertainty of future changes to burn windows (Prichard et al., 2017; Wimberly and Liu, 2014) but contrast with claims that climate change will cause, or already is causing, a decrease to the number of burn windows in temperate forests (Williamson et al., 2016; Ximenes et al., 2017). Our results do not exclude the possibility of declines in weather conditions favourable for prescribed burning, but they do limit declines to certain regions and seasons (e.g. parts of central and northern Coastal NSW during autumn). Our results are consistent with the hypothesis of increased availability for burning during winter (Rocca et al., 2014) and the hypothesis that increasing climate variability will cause a decrease in the coincidence of suitable weather and fuel moisture (Mitchell et al., 2014).

Our results contrast strongly with the only previous quantitative estimate of climate change impacts on prescribed burn windows for coastal NSW (Clarke and Evans, 2018). While both studies found the potential for increases and decrease in autumn, the magnitude of change estimated by Clarke and Evans (2018) was much larger (-11 to +10 days) compared to our study (−6.2 to +4.4 days, depending on the weather definition used). Clarke and Evans (2018) projected considerable changes during winter (around −15 to +20 days), compared to much smaller and universally positive changes in our study (0.0 to +7.9 days). Clarke and Evans (2018) projected mostly decreases (-10 to +3 days) during spring (September-November), whereas we projected largely increases during the spring burning season of August-October (-0.1 to 8.3 days). Given that both studies cover a similar study area and draw on the same regional climate model ensemble (Evans et al., 2014), the differences are likely almost entirely due to the different definitions used. While Clarke and Evans (2018) used a single, simplified definition ($3 < \mathrm{FFDI} < 12$), we used multiple multivariate definitions drawn from the scientific literature, weather observations on the day of actual prescribed burns and operational guidelines. These more realistic and comprehensive definitions are likely to be more representative of the conditions under which prescribed burning is currently conducted.

By utilising an ensemble of climate model projections and multiple weather definitions, we aimed to investigate some of the uncertainty in potential responses of prescribed burning weather conditions to climate change. Choice of weather definition clearly influences the magnitude and direction of future changes. The Operational definition has a much narrower range of changes than the other definitions, perhaps because

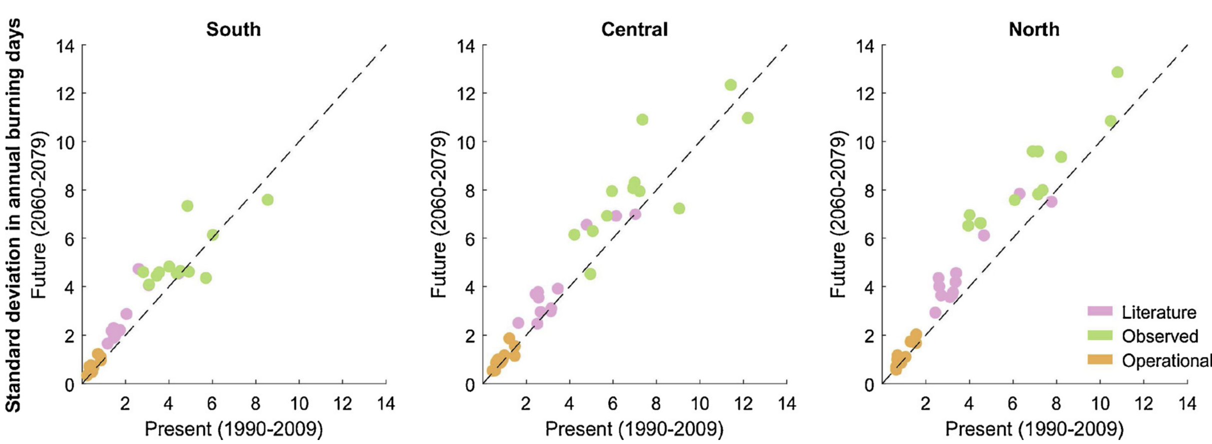

Fig. 4. Standard deviation in annual prescribed burning days for present (1990–2009) and future (2060–2079) periods for each of the 12 ensemble members. Burning days are calculated using the Literature, Observed and Operational definitions. Results are shown for the South, Central and North regions. Dotted lines show equality.

of its more stringent upper limits to temperature, wind speed and daily FFDI (and a more stringent lower limit to relative humidity). Conversely, the Observed definition allows for a greater range of temperature, wind speed and fuel moisture values than the other definitions, which explains the greater range in projected changes in most cases. The climate model ensemble was selected partly to span a range of potential future climates in NSW, including both decreases and increases in annual rainfall, and a range of temperature increases (Evans et al., 2014). While rainfall was not a variable in any of the definitions used here, it is used in the calculation of FFDI (via DF) and can display moderate correlations to humidity and fuel moisture. Rainfall is therefore a reasonable candidate for explaining some of the variability in projected changes to burning days. So are relative humidity and wind speed, for which the range of projected changes in 3 pm values in this region also spanned positive and negative values (Clarke and Evans, 2018). Conversely, temperature is not likely to have accounted for much of the variation in projected changes as it increased in all 12 ensemble members. However, it is possible that the general warming trend could be driving moderate increases in burning days in winter months, somewhat analogous to upslope range-shifts predicted for some montane species (Chen et al. (2011)). Weaknesses in the ability of DF to properly quantify fuel moisture conditions (Resco de Dios et al., 2015) introduce uncertainty about the true conditions during recorded prescribed burning (and hence derived definitions) and the effect of projected climate changes. Future studies could attempt a formal analysis of the relative contribution of individual variables to overall changes in burning days, although this is complicated by the number of variables involved and their frequent collinearity. Preliminary analysis suggests that there are few cases where a single variable is responsible for most of the change (data not shown). Two results that merit further investigation are latitudinal gradients in the upper end of projections for burning days in spring, and in the lower end of projections in autumn – patterns that were present in all three definitions. In spring the potential increases were greatest in the North and smallest in the South, while in autumn potential decreases were greatest in the North and smallest (actually positive) in the South.

4.1. Limitations

We did not explore all possible weather definitions. Other constructions of ideal conditions for prescribed burning in DSF are possible, as are other definitions of actual conditions (e.g. through selection of different variables or percentiles). The Operational definition we used has regional variants incorporating local conditions which merit exploration. Weather definitions based on desired fire size are possible, although in deriving our Observed definition, classification by fire size did not substantially alter threshold values. An important limitation of the Observed definition is that it does not necessarily reflect the prevailing weather on the fire ground. Such data is not routinely collected but would be useful for various analyses, from smoke and greenhouse gas emissions to fire severity (Storey et al., 2016). It is also possible that forecasts, rather than observations, would provide a better indication of the conditions under which burning is planned. Future studies could consider wind direction or variables related to atmospheric stability or dispersion (Chiodi et al., 2018). We did not analyse the sensitivity of burning days to the threshold values used for each variable, including the possibility that some thresholds could be defined in relative rather than absolute terms. Analyses could be expanded to other areas and vegetation types, additional emissions scenarios, as well as the use of climate and weather data with sub-daily resolution, to allow for a finer-grained analysis of window length (Monzon-Alvarado et al., 2014).

4.2. Future implications

This study provides a quantitative estimate of the impact of climate change on prescribed burning weather conditions in south-eastern Australia using realistic definitions of the weather windows. It suggests that decreases in the window of opportunity for conducting prescribed burning are not inevitable. Instead, there is the possibility of a range of complex changes in magnitude and seasonality, including increases in the major prescribed burning seasons of autumn and spring. This suggests that suitable conditions for prescribed burning in dry sclerophyll forests will persist under climate change. However, practitioners should understand their exposure to changes in the frequency and seasonality of prescribed burning days, not just for their own operations but for those with whom they share resources. Changes in the relative frequency of autumn and spring burns could have implications for the types of burns conducted, as larger burns are more likely to be undertaken in autumn than spring to minimise the risk of fires escaping as fire weather conditions worsen in summer. In all scenarios investigated, interannual variability persists or increases moderately under climate change, which poses challenges for prescribed fire planning and also makes the detection of any trends the number of burning days more difficult. An important implication for management is that climate change impacts on prescribed burning days are highly dependent on the precise construction of the weather definition. A better understanding is needed of the interaction between weather and prescribed burning as it is currently practiced, including the degree to which variables and thresholds set hard limits on conducting safe and effective burns and the conditions under which otherwise stringent definitions may be relaxed. This understanding could also be improved with the development of physically-based modelling and monitoring methods that can quantify variation in dead and live fuel moisture content within prescribed burn blocks.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agrformet.2019.03.005.

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